NPS ME-90-07

NAVAL POSTGRADUATE SCHOOL
Monterey, California

A Predictive Method to Describe the Boiling Behavior of Refrigerant-oil Mixtures

By

John R. Lloyd
Visiting Professor (1)

and

Paul J. Marto
Distinguished Professor

December 31, 1990

Approved for Public Release; Distribution Unlimited

Prepared for: David Taylor Research Center

Annapolis, Maryland

NAVAL POSTGRADUATE SCHOOL
Monterey, California

Rear Admiral R.W. West, Jr.
Superintendent

H. Shull
Provost

This report was prepared for the David Taylor Research Center, Annapolis, Maryland and funded by the Naval Sea Systems Command.

This report was prepared by:

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION / AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED
2b DECLASSIFICATION / DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) NPS ME-90-07	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION NAVAL POSTGRADUATE SCHOOL 6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION DAVID TAYLOR RESEARCH CENTER
6c ADDRESS (City, State, and ZIP Code) MONTEREY, CA 93943	7b ADDRESS (City, State, and ZIP Code) ANNAPOLIS, MD 21402
8a NAME OF FUNDING / SPONSORING ORGANIZATION NAVAL SEA SYSTEMS COMMAND 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N0002490WR02886
8c ADDRESS (City, State, and ZIP Code) Washington, DC 20350	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO / PROJECT NO / TASK NO / WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification)
A PREDICTIVE METHOD TO DESCRIBE THE BOILING BEHAVIOR OF REFRIGERANT-OIL MIXTURES

12 PERSONAL AUTHOR(S)
JOHN R. LLOYD AND PAUL J. MARTO

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
FINAL	FROM 4-1-90 TO 9-30-90	1990 DECEMBER 31	35

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	BOILING, REFRIGERANTS, OILS, MIXTURES

19 ABSTRACT (Continue on reverse if necessary and identify by block number)
The need for efficient and environmentally safe refrigerants is of great concern to the Navy, and is driving them to explore the performance of alternate refrigerants for use in shipboard evaporators. Each time a new refrigerant is considered, one must also consider how oil contamination will affect its performance. The present study surveys the literature for a predictive technique to calculate the nucleate boiling heat transfer behavior of refrigerant-oil mixtures that is fundamental to the operation of refrigerant systems. There were three expressions found that could be considered for use. These expressions for the nucleate boiling heat transfer were empirically based formulations, which means that a new series of experiments must be conducted every time a different refrigerant-oil combination is considered for use. An expression that is currently under development for mixtures in general was found that is based only upon the thermophysical properties of the fluids and their mixtures. No empirical constants are necessary. The mass diffusion coefficient of the oil in the refrigerant is found to be the key property

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL PAUL J. MARTO	22b TELEPHONE (Include Area Code) (408) 646-3241 22c OFFICE SYMBOL

DD Form 1473, JUN 86 *Previous editions are obsolete* SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

to be measured in order to evaluate the predictive capability of this expression. Experiments are proposed to obtain this key property and then to test the predictive capability of this expression. Modifications to this expression will be developed as the experiments indicate are necessary.

(1) University Distinguished Professor and Chairperson, Department of Mechanical Engineering, Michigan State University, East Lansing, Michigan 48824-1226

A Predictive Method to Describe the Boiling Behavior of Refrigerant-Oil Mixtures

by

John R. Lloyd
Visiting Professor (1)

and

Paul J. Marto
Distinguished Professor

Naval Postgraduate School
Monterey, California 93943

December 31, 1990

ABSTRACT

The need for efficient and environmentally safe refrigerants is of great concern to the Navy, and is driving them to explore the performance of alternate refrigerants for use in shipboard evaporators. Each time a new refrigerant is considered, one must also consider how oil contamination will affect its performance. The present study surveys the literature for a predictive technique to calculate the nucleate boiling heat transfer behavior of refrigerant-oil mixtures that is fundamental to the operation of refrigerant systems. There were three expressions found that could be considered for use. These expressions for the nucleate boiling heat transfer were empirically based formulations, which means that a new series of experiments must be conducted every time a different refrigerant-oil combination is considered for use. An expression that is currently under development for mixtures in general was found that is based only upon the thermophysical properties of the fluids and their mixtures. No empirical constants are necessary. The mass diffusion coefficient of the oil in the refrigerant is found to be the key property to be measured in order to evaluate the predictive capability of this expression. Experiments are proposed to obtain this key property and then to test the predictive capability of this expression. Modifications to this expression will be developed as the experiments indicate are necessary.

(1) University Distinguished Professor and Chairperson, Department of Mechanical Engineering, Michigan State University, East Lansing, Michigan 48824-1226

A Predictive Method to Describe the Boiling Behavior of Refrigerant-Oil Mixtures

by

John R. Lloyd (1)
Visiting Professor

and

Paul J. Marto
Distinguished Professor

Naval Postgraduate School
Monterey, California

(1) University Distinguished Professor and Chairperson, Department of Mechanical Engineering, Michigan State University, East Lansing, Michigan 48824-1226

INTRODUCTION

The energy crisis of the 1970's brought an awareness of the need to design more energy efficient systems. The emergence of the environmental concern over the greenhouse effect during the 1980's brought an awareness of the need to find and use less environmentally toxic substances in thermal design, especially in the design of refrigeration systems. These two forces have had a major impact on the air conditioning and refrigeration industries, and have caused the Navy to search for more energy efficient, less environmentally toxic refrigeration fluids for the refrigeration systems which are on board ships and submarines.

Refrigerant R-114 has been the recent focus of research at the Naval Postgraduate School [1-4] because: (1) its operating pressure is close to atmospheric pressure; (2) it is highly stable with respect to temperature; and (3) it is relatively low in toxicity. Under this research program, extensive nucleate boiling experiments have been carried out to explore three important topics relative to the use of R-114 in large refrigeration systems. First, the boiling heat transfer characteristics of pure R-114 have been determined. Second, the effect of oil contamination up to 10% on its heat transfer characteristics have been revealed, and third, the effects of boiling surface enhancement on heat transfer have received attention. These studies have provided considerable understanding of the various phenomena involved with the increase in heat

transfer due to enhancement effects and with the degradation in heat transfer due to the introduction of contaminant fluids in the boiling process. There have not been any fundamental-based predictive models developed that have been used to describe these processes for various refrigerant-oil mixtures, operating conditions or enhanced surfaces.

Recently, refrigerant R-124 has received attention in the Navy because it is believed to be less toxic to the environment than R-114. Its operating pressures are reasonable, and its degradation properties relative to temperature are believed to be acceptable. If R-124 is to be used in ship-board refrigeration systems, Zerol 300 oil, which is different from that used in the previous studies, will most likely be employed. Obviously, if there were a good, fundamental-based predictive model of nucleate boiling heat transfer that includes the effects of surface enhancement and oil contamination, it would be of great value as this new refrigerant-oil combination or other alternative combinations are being considered.

Modeling of the process of multicomponent fluids has received little attention as compared to boiling of single pure fluids. In all cases, it has been found that the presence of a second component degrades the heat transfer as compared to either of the pure components, but that modification of the surface from the normal "smooth" character can either increase or decrease the heat

transfer [5]. There are no fundamental-based, truly predictive expressions that have been developed to describe the boiling heat transfer process for multicomponent refrigerant-oil fluids, even for smooth surfaces much less enhanced surfaces [6].

The goals of the present study were to: (1) perform an exhaustive search of the archival literature for studies of heat transfer due to boiling of refrigerant-oil fluids; (2) evaluate any predictive correlations discovered; (3) idenitify appropriate experiments to enable the development of the fundamental-based predictive model; (4) design experimental facilities to verify the predictive capability of the derived model for smooth surfaces; and (5) design experiments to study the effects of surface enhancement on the boiling heat transfer of the refrigerant-oil fluid combinations.

LITERATURE SURVEY

There have been many publications dealing with the presentation of data for boiling heat transfer of refrigerant-oil mixtures. There have only been four works that have attempted to develop correlations to describe the observed heat transfer. In this survey, these four references will be discussed in detail, but the other studies will be referenced only as needed to support the present work.

In 1979 Chongrungerong and Sauer [7] published the first correlation of heat transfer for the boiling of refrigerant/oil mixtures. They studied the case where a prescribed heat flux was applied to a single smooth tube. They included the mixture Prandtl number, the heat of vaporization of the volatile substance, the effect of bubble density compared to that of the liquid, the applied heat flux and the effect of pressure in the development of their correlation. They proposed the following expression for the heat transfer for the boiling of R-11/oil mixtures:

$$h=0.0523\left[\left(\frac{(Q/A)D}{(\mu_L \Delta h_{fg})}\right)^{0.569}\left(\frac{(\mu_L c_L)}{k_L}\right)^{0.395} P^{1.695}\left(\frac{D}{0.01588}\right)^{-0.444}\left(\phi_f \frac{\rho_L}{\rho_v}\right)^{1.579}\right] \quad (1)$$

where:

ϕ_f = Volume fraction of pure refrigerant

D = Tube diameter (m)

P = Pressure (atm)

Q/A = Applied heat flux (W/ m^2)

h = Heat transfer coefficient (W/m^2)

μ_l = viscosity of the liquid (g/m-s)

c_L = Specific heat of the liquid (KJ/g-K)

k_L = thermal conductivity of the liquid (W/m-K)

Δh_{fg} = latent heat of vaporization (W-s/g)

$\rho_{L,v}$ = density of the liquid and vapor (g/cm^3)

The assumptions behind this model were that the properties were those of the pure refrigerant or the refrigerant-oil mixture as appropriate, the mixture was an ideal mixture (homogeneous and no chemical reactions) and the operation of the boiling process was steady. To develop the correlation, they performed experiments with R-11 as the refrigerant, and they used 3GS, 4GS and 5GS oils in concentrations ranging from 0% to 10%.

They attempted to compare their equation with a variety of data that were available, but they were unable to do this because there were problems in finding the appropriate mixture properties that were used in the various experiments. They therefore selected some typical properties and then simplified their equation to the expression given below:

$$h = 6.17\,(Q/A)^{0.55}\phi_f^{3.65}P^{0.24} \qquad (2)$$

Chongrungreong and Sauer [1] actually found that equation (2) did a better job of predicting the heat transfer for the higher oil

concentrations than the more complete equation (1) did. They found that equation (1) came within 43% of all of the published data where the property information was available. The worst agreement came with R-11 and the highest oil concentrations, approximately 10%. Equation (2) only had a maximum error of 25% at the 10% oil concentrations. The better agreement of equation (2) is due in part to the selection of their properties.It is important to note that they did not model the physical processes accurately. For example, the assumption of the ideal mixture does not allow for concentration gradients to build up around the bubbles, and therefore the mass transfer process which moves oil away from the bubble and moves refrigerant to the bubble, which can be significant at high oil concentrations, is not accounted for at all.

In 1982 Stephan and Mitrovic [8] presented a nice discussion of the physics involved in the mixture boiling process. They assumed that the refrigerant-oil mixture could be modeled as a binary mixture. They proceeded to explain what is happening by referring to a phase equilibrium diagram as shown in Figure 1. Plotted in this figure is temperature versus the mole fraction of the less volatile component of the mixture, which in this case is the oil. The dew-point line and the boiling-point lines are drawn. They represent the locus of states which describe the mixture vapor as found in the bubble and the liquid at the initiation of the boiling process respectively.

To understand what physical phenomena are important to include, one must understand what happens during the boiling of mixtures. Consider a mixture that has oil concentration X_A. The bubble starts to form at point A on the diagram, but the temperature of this mixture rises to point B as a result of the boiling process. This creates a situation where the liquid at the bubble interface has concentration shown by point C and the vapor is at point D. In reality, the formation and release of the bubble from the surface causes the generating surface to cool slightly, and as a result the actual "bubble state" moves to a lower temperature at a slightly elevated oil concentration as seen at point E. The surface then heats up again and the bubble returns to state B. This process repeats itself as the boiling process continues [8]. When the dew-point and bubble-point lines are close together, the variations in concentration between the vapor and the liquid at the interface are small. On the other hand, when the curves are widely separated, the effects of oil concentration gradients can become very substantial. This is expected to be the case for most refrigerant/oil combinations that are commonly used.

One assumption that is usually made in modeling the mixture boiling process is that the mixture concentration is uniform around the bubble, as we saw in reference [7]. Adjacent to any surface which is transferring heat to its surroundings is a thermal boundary layer of some finite thickness. When the bubble is of such a size as to be significant relative to the boundary layer thickness, we

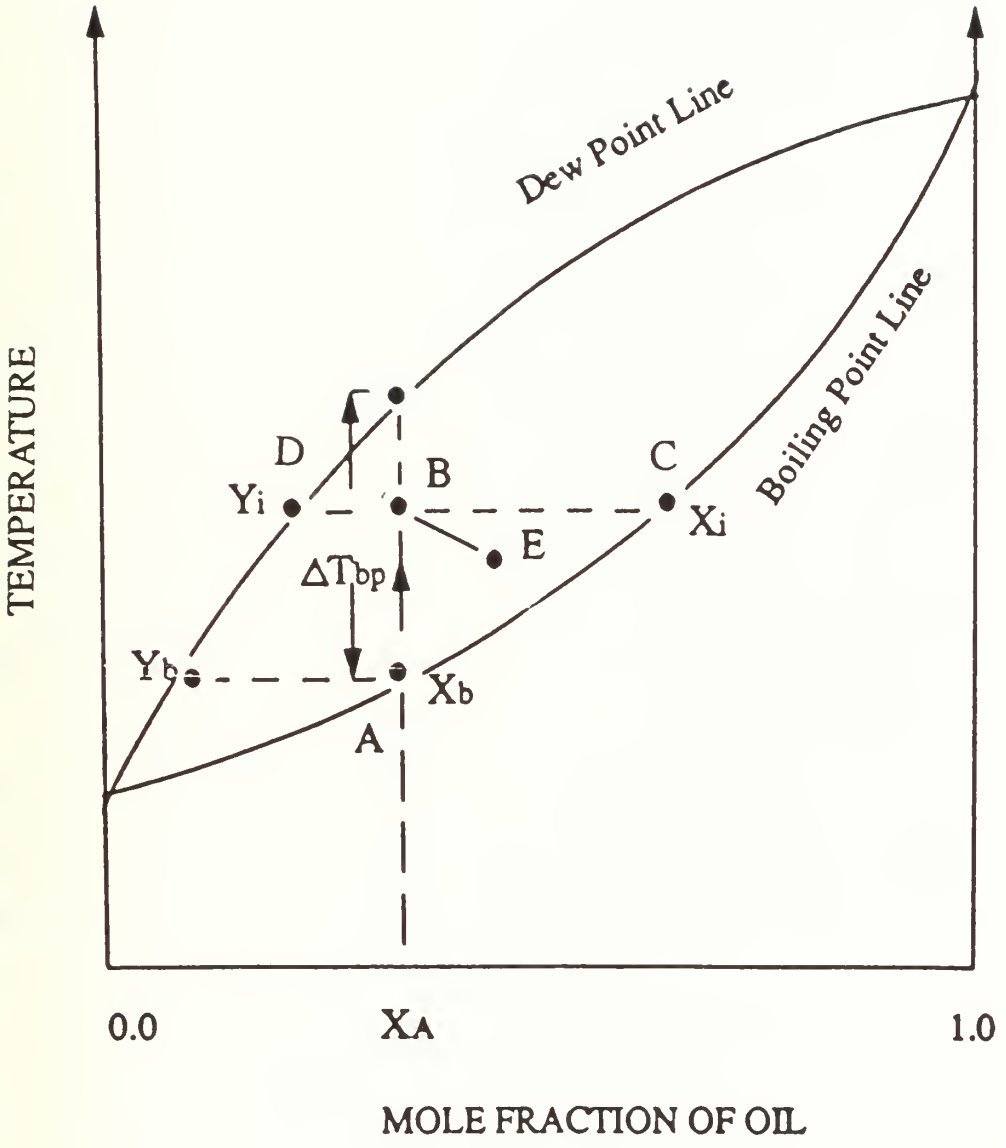

Figure 1. Vapor-Liquid Equilibrium Diagram

can be sure that the assumption of uniform bubble temperature, and as a result the assumption of spherical shape, are not strictly correct. As a result, there are nonuniform flows around the bubble, and the heat transfer around the bubble is not uniform. All these observations result in the realization that the concentration of the fluid surrounding the bubble is not uniform either and therefore models that make no attempt to consider the effects of variations in mass transfer around the bubbles will be doomed to fail at higher oil concentrations.

In 1984 Hahne and Noworyta [9] presented a new correlation for heat transfer for nucleate boiling of refrigerant/oil mixtures. They developed an empirical expression that related the heat transfer coefficient to the applied heat flux, and in doing so, took the oil concentration to be the only variable other than the applied heat flux. All explicit effects due to temperature variations, variable properties and such were contained in three empirical coefficients as shown in Equation (3).

$$h=0.085\left[\exp(b_1 w)+\exp(b_2 w)\right] q^{(0.89-Bw)} \tag{3}$$

where h, q and w, the oil mass concentration, are in SI units.

They used refrigerant R-11 and Clavis G100, Clavis G68 and Oil 22-12 in concentrations up to 20%. In this equation b_1, b_2 and B are empirical coefficients with units inverse to those of the mass

concentration. Hane and Noworyta give values of these coefficients for each refrigerant-oil combination studied.

As one might expect, their empirical predictions agree quite well with the data since they were not trying to make the coefficients general for all mixtures. The main drawback with this approach is that the experiments must be conducted with every new refrigerant-oil combination. It is also only valid over the concentration range tested; the predictions are only as good as the experiments where the coefficients were determined; and, the only parameter beside the applied boundary condition is the oil concentration. It leaves out explicit descriptors for the physical parameters that characterize the physical phenomena of the boiling process.

In 1984 Jensen and Jackman [10] presented a model of nucleate boiling of refrigerant/oil mixtures which does the best job of accounting for the physical phenomena that has been published to date. They began with the assumption that the variable property effects were the most important phenomenon to account for. They assumed that there was at the time of bubble departure an oil enriched layer around the entire bubble. Underlying this assumption is another assumption, that the refrigerant is the vaporized substance contained inside the bubble. They chose the time of bubble departure as a parameter because there is information on time to departure and because at that time the bubble is approximately round. They assumed that the mass boundary layer was

uniform despite the fact that the bubble was still touching the surface at the time of departure.

In order to account for the variation in oil concentration around the bubble, they used the concept of an effective oil concentration that was higher than the bulk concentration. The expression that they used was

$$C_{eff}=\frac{\frac{C\rho_v d}{(1-C)}+C\rho_m(6d^2z+12dz^2+8z^3)}{\frac{C\rho_v d^3}{(1-C)}+\rho_m(6d^2z+12dz^2+8z^3)} \quad (4)$$

where

C = bulk mass oil concentration ($kg_{oil}/kg_{mixture}$)

ρ_v = Density of the vapor in the bubble (g/ cm^3)

d = Diameter of bubble at departure (m)

z = Thickness of mass boundary layer around bubble (m)

This expression was simplified to

$$C_{eff}=C(1+0.0317\Delta T_{sat}^{0.753}) \quad (5)$$

with temperature in K.

This value for the effective oil concentration was then used in the heat transfer expression

$$\frac{h}{h_z}=\exp(-4.095C_{eff}-55.11C_{eff}^2) \tag{6}$$

where the value of h_z in SI units is given by Forster and Zuber [11]

$$h_z=0.00122\left[\frac{k_l^{0.79}c_{pl}^{0.45}\rho_l^{0.049}g_c^{0.25}}{\sigma^{0.5}\mu_l^{0.29}h_{fg}^{0.24}\rho_v^{0.24}}\right]\Delta T_{sat}^{0.24}\Delta P_{sat}^{0.75} \tag{7}$$

As stated previously, this expression for boiling heat transfer of refrigerant-oil mixtures has the strongest base in the physics of the boiling phenomena. While this is so, it is interesting to note that, for R-113 and R-11 refrigerants with four different oils, this expression has an absolute error when compared to the data presented of 29.6%. The authors attribute the error to the scatter of the data and the lack of information on mixture properties, especially the mass diffusivity.

Jensen and Jackman state that mass diffusion effects are very

important, especially at higher oil concentrations. They also conclude that viscosity and surface tension are the two properties that they measured that behaved least like the ideal mixture would. The mass diffusion process is the least understood property and is key to accurate predictive models in the future.

It is clear from the above discussion that none of these models have accurately taken into account all the significant physical phenomena that are present in nucleate boiling of refrigerant-oil mixtures. The effects of mass diffusion, thermal diffusion, the interactions of these two processes, variation of mixture properties, transfer processes around the bubbles prior to departure from the surface and surface geometry effects are all open questions.

PHYSICS-BASED MODEL

Because there have been no models developed to date for refrigerant-oil mixtures which take the important physical phenomena and parameters into account, it is appropriate to turn to the literature for general mixtures. The fundamental physical processes are the same for all mixtures. The important thing is to identify which processes dominate the boiling of each combination of fluids. As stated by Thome [6], there is no model published to date that is comprehensive in its approach to modeling all the

physical processes that go on in the refrigerant-oil mixture problem.

The approach that has included the most physics in its derivation for mixtures in general is a study that was developed by Bajorek [12] and is currently in preparation by Bajorek, Lloyd and Thome [13]. This model begins with the binary mixture models put forth by Schlünder [14] and by Thome and Shakir [15]. First, it is assumed that a refrigerant/oil mixture can be considered to be a binary mixture of pure fluids. This is a reasonable assumption since refrigerants and oils do not react with each other to any significant extent at temperatures characteristically found in the nucleate boiling range. Assume that the mixture is adjacent to a surface that is hotter than the boiling temperature of the mixture at that pressure.

At a nucleation site a bubble will begin to form. This bubble is the vapor of the refrigerant since it is significantly more volatile than the oil under consideration. At the vapor/liquid interface of the bubble, the concentration of the refrigerant is depressed below that of the bulk due to the mass transfer process which must take place to move the refrigerant to the bubble surface, and at the same time, the concentration of the oil increases above that of the bulk as required by continuity. This would be uniform around the bubble if these processes were controlled simply by diffusion of mass and energy. Because this

takes place at a surface and therefore in a boundary layer in a gravitational field, convection becomes a player in the boiling process, and the temperature and species concentrations will vary around the bubble. To properly account for all these effects would be a very difficult analysis. We must simplify the analysis.

Consider the schematic diagram of a bubble forming at a surface as shown in Figure 2. In the actual problem, the bulk temperature of the mixture varies over the diameter of the bubble; the heat transfer varies over the surface of the bubble; the mass concentration of the bulk fluid varies due to the presence of the wall and the convective heat and mass transfer rates at the surface of the bubble vary around its circumference due to the bouyancy created by the variations in temperature and species concentration. One must make some assumptions in order to begin to solve this problem.

Following the analysis of Schlünder [14] and Thome and Shakir [15], one defines an ideal heat transfer coefficient by

$$h_{id}=q''/(T_i-T_b) \tag{8}$$

and an overall heat transfer coefficient by

$$h=q''/(T_w-T_b) \tag{9}$$

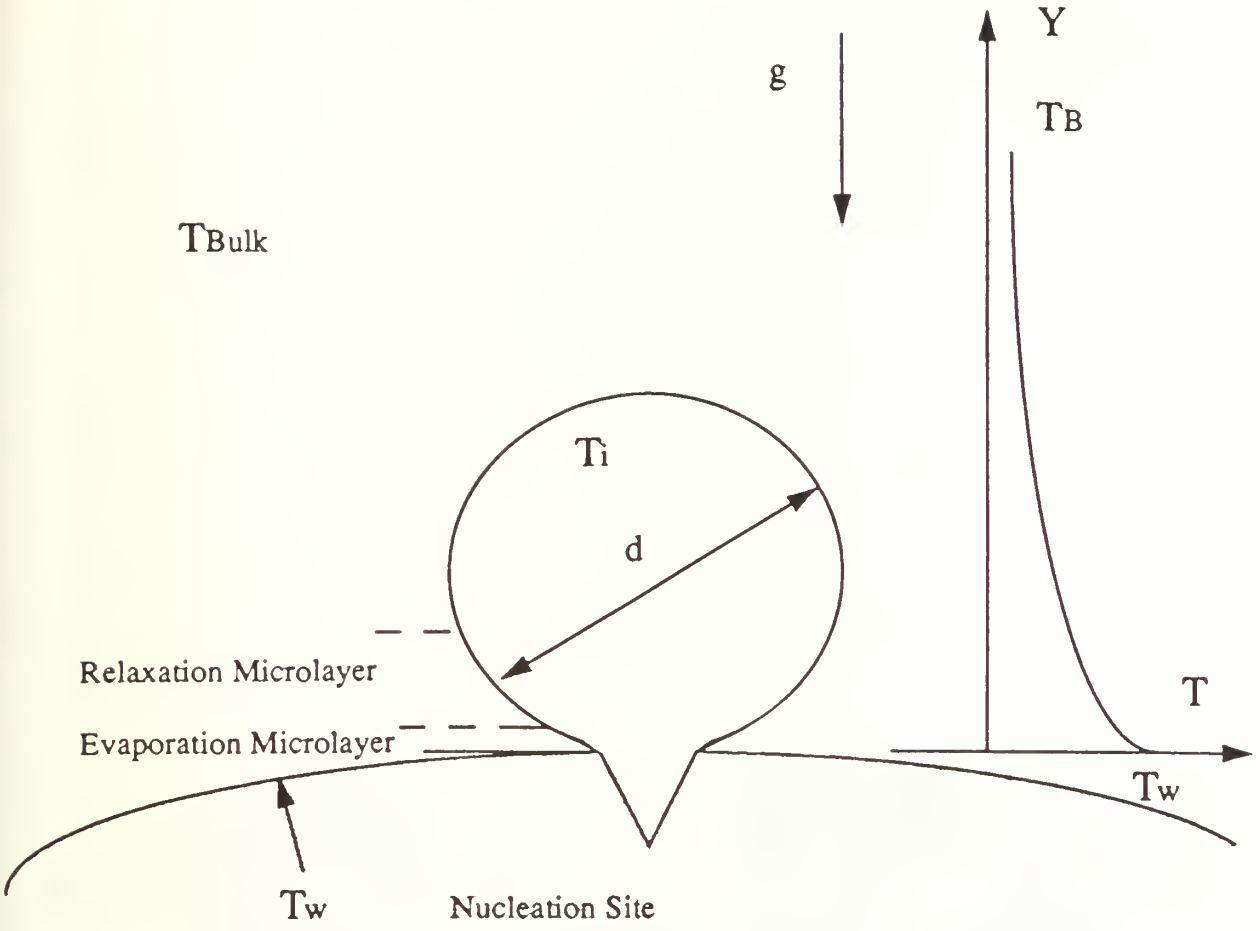

Figure 2. Model of Bubble During Growth

Then it can be shown that

$$\frac{h}{h_{id}} = [1 + \frac{T_i - T_b}{T_w - T_b}]^{-1} \tag{10}$$

It was shown by Thome and Shakir [6] that

$$(T_i - T_b) = \frac{\Delta T_{bp}}{(y_i - x_i)} (x_b - x_i) \tag{11}$$

where x_i and y_i are from Figure 1. They then made the approximation

$$(T_i - T_b) = \Delta T_{bp}[1 - \exp(-\psi)] \tag{12}$$

where ΔT_{bp} is defined in Figure 1, and ψ is a function of thermodynamic variables and accounts for the degradation in heat transfer due to the mass transfer process. This enabled them to derive the following equation for the nucleate boiling heat transfer coefficient

$$\frac{h}{h_{id}} = \{1 + \frac{h_{id}}{Q/A} [\frac{dT}{dx} (y_i - x_i) [1 - \exp\Psi]]\}^{-1} \tag{13}$$

Bajorek et al [13] assumed the existence of an evaporation microlayer between the surface and the bubble. Above that is a relaxation microlayer which reaches around the bubble to where the bulk fluid exists. They further assumed that the temperature

profile in the fluid, between the wall and the bubble, in the evaporation microlayer is linear. Given those assumptions they derived an expression for ψ

$$\psi = \frac{kq''}{\rho \Delta h_v D_{12} h_{id} (\kappa / D_{12})^{0.5}} \qquad (14)$$

where the properties are in SI units.

Assuming $(y_i - x_i) = (y_b - x_b)$, then the expression for nucleate boiling heat transfer for the binary mixture is

$$\frac{h}{h_{id}} = \{1 + \frac{h_{id}}{Q/A} [\frac{dT}{dx} (y_b - x_b) [1 - \exp(\frac{-kQ/A}{\rho \Delta h_v D_{12} h_{id} (\leq)^{1/2}})]]\}^{-1} \qquad (15)$$

The predictions based on this expression were compared to the data of Bajorek [12] for acetone/water and ethanol/water mixtures. This expression was able to predict the data to 9% on the average with a standard deviation of 32%.

The question of importance at this point is whether or not equation (15) is based upon the correct physical phenomena that govern the nucleate boiling process for refrigerant-oil mixtures. This can only be determined by comparing data against the prediction. In order to make these comparisons, the surface temperature, the bulk

mixture temperature, the bulk mixture oil concentration, the phase equilibrium curves, the pure component boiling temperatures, the bulk mixture thermal conductivity and density, the bubble interface temperature, the thermal diffusivity and the diffusion coefficient of oil in refrigerant must all be known. We do not know this information for even one of the tested refrigerant-oil mixtures, and so some very important experiments to find the key mixture properties must be designed. The most difficult property is the diffusion coefficient for the oil in the refrigerant and the thermal diffusivity and conductivity.

The important point to realize at this time is that we have an expression for the nucleate boiling heat transfer which contains no empirical coefficients. What remains is to evaluate its predictive capability for refrigerant-oil mixtures. To do this we must develop the instrumentation to measure the required mixture properties.

REFRIGERANT-OIL MIXTURE PROPERTY MEASUREMENT

In the derivation of equation (15) it was assumed that the heat transfer to the bubble takes place in the evaporation microlayer and therefore the relaxation microlayer is comparatively unimportant. This means that the ideal heat transfer coefficient, h_{id}, is simply the mixture thermal conductivity divided by the microlayer thickness. It is possible to measure this coefficient if

the bubble vapor temperature can be measured. This can in principle be done using interferometry. Of course, then the evaporation microlayer thickness could also be measured. These measurements would represent a major contribution to the field. In the absence of these experiments one could also experimentally determine the vapor equilibrium curve for each mixture and from that estimate the bubble interface temperature.

No matter what is done, the diffusion coefficient for the oil through the refrigerant must be determined. The rest of the properties of interest needed to test the heat transfer relationship of equation (15) for some refrigerants are available in the literature.

PROPOSED EXPERIMENTS-

Diffusion Coefficients

As indicated above, the key property that must be determined to predict the heat transfer for nucleate boiling of refrigerant/oil mixtures is the diffusion coefficient. The measurement of this property has not been accomplished for any refrigerant/oil mixture, and so any data will represent a significant step forward in this important problem.

In order to make these measurements, the technique outlined by Bidlack [16] will be used. In this experimental technique, a Mach-Zehnder interferometer is used to measure the variation of refractive index of the refrigerant due to the diffusion of the oil into it. Conceptually the experiment is quite simple. Figure 3 shows a schematic of a test cell where one creates a sharply defined layer of oil beneath a layer of refrigerant. There is an infinite gradient at the interface between the two liquids at time zero, and the liquids can be assumed infinite in extent relative to the interface. As time proceeds, the oil diffuses into the refrigerant, thereby changing its refractive index. If one takes an interferogram at time zero and then at several time intervals, it is possible to measure the process of diffusion as a function of time. Figure 4 shows a schematic of a typical interferrogram at some time t. With proper analysis of this one can obtain the binary diffusion coefficient as follows.

Consider the case where the interface between the refrigerant and the oil is infinitely sharp and is located at $x = 0$. For $x > 0$ the fluid is refrigerant. For $x < 0$ the fluid is oil. At time zero, the oil begins to diffuse into the refrigerant, and the refrigerant begins to diffuse into the oil. Because the diffusion of A into B is the same as B into A, the diffusion front moves out equally in both directions from $x = 0$. Fick's Second Law describes this

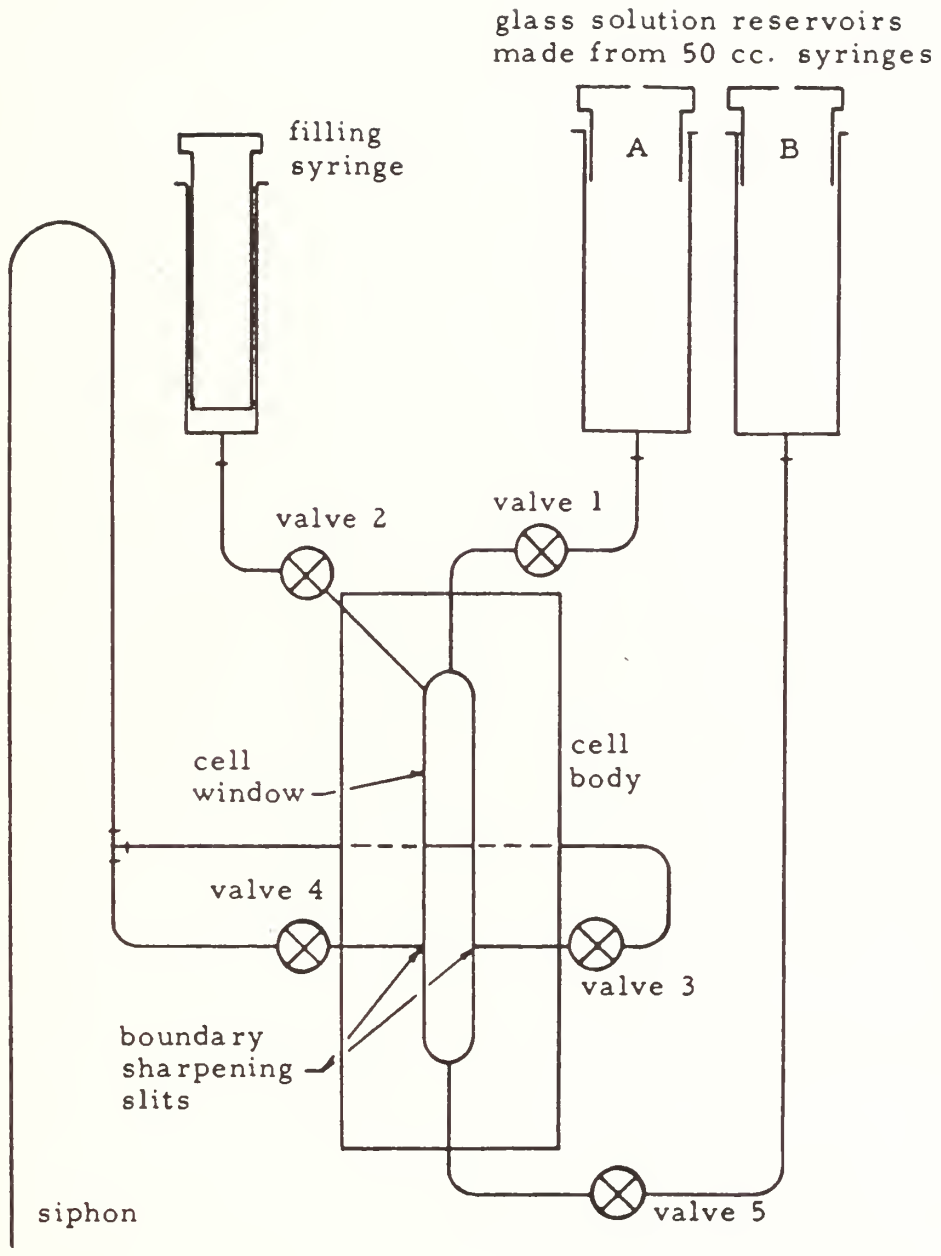

Figure 3. Diagram of Diffusion Cell (From Reference [16])

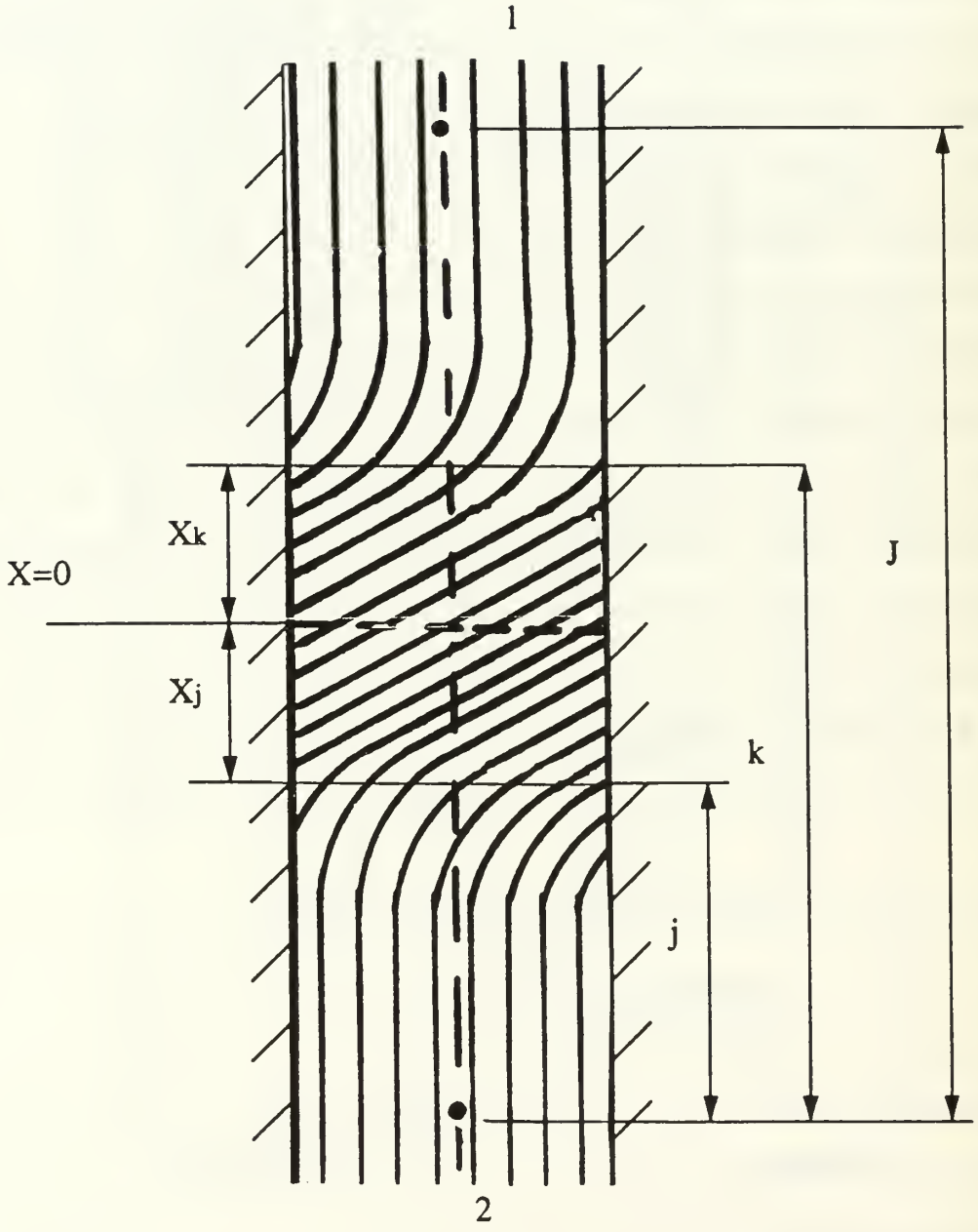

Figure 4. Schematic of Typical Interferogram at Time t (From Reference [16])

process and is given as follows:

$$\frac{\partial^2 c}{\partial x^2} = \frac{1}{D_{12}} \frac{\partial c}{\partial t} \tag{16}$$

with the boundary conditions:

Case 1:

For x>0 $x \rightarrow \infty$ $t \geq 0$ $c = c_1$

$t = 0$ $c = c_1$ $\infty > x > 0$

$x = 0$ $c = (c_1 + c_2)/2$ $t \geq 0$

Case 2:

For x<0 $x \rightarrow -\infty$ $t \geq 0$ $c = c_2$

$t = 0$ $c = c_2$ $0 > x > -\infty$

$x = 0$ $c = (c_1 + c_2)/2$ $t \geq 0$

The assumptions for this are that the concentration dependence of D_{12} is negligible and that the diffusion gradient has the properties of the normal distribution [16].

If one notes that the concentration is directly proportional to the

refractive index, n, then the solution of this problem for any time t is as follows:

$$\frac{(c-c_0)}{(c_2-c_1)} = \frac{1}{2} erf(x/\sqrt{4D_{12}t}) = \frac{(n-n_0)}{(n_2-n_1)} \qquad (17)$$

If one defines the magnification of the interferogram to be M, as shown in Figure 4, then one can rewrite Equation (17) as

$$D_{12}t = \frac{1}{4M^2}\left[\frac{x_j^1+x_k^1}{erf^{-1}\left(\frac{J-2j}{J}\right)+erf^{-1}\left(\frac{2k-J}{J}\right)}\right]^2 \qquad (18)$$

In this equation J is the total number of fringes from the top of the interferrogram to the bottom, k and j are the local fringe numbers and the x' quantities are the fringe spacings as measured on the actual interferrogram. They are related to the true dimensions through the magnification factor by x'= Mx.

This is simplified by simply defining the squared term to be GRADSQ. If one plots GRADSQ vs time then the SLOPE of the curve provides the diffusion coefficient.

$$D_{12} = \frac{SLOPE}{4M^2} \qquad (19)$$

The diffusion coefficient defined this way is assumed then to be

that of the mixture at the average concentration between the upper and lower fluids in the test section [16]. The accuracy depends upon the ability of the experimenter to create a step change in concentration at the interface of the two fluids as well as to measure the fringe locations. Bidlack claims that the error is within 1% [16].

Thermal Diffusivity

The thermal diffusivity of the mixture must also be determined. This can be done using standard Differential Scanning Calorimetery techniques. In this technique, a small sample of the mixture is placed in a special cup that is is turn placed in the heating section of the instrument. At time zero, a prescribed heat flux is applied and the time response of the fluid sample temperature is monitored. Since the sample cup is calibrated, the fluid thermal diffusivity is the only unknown in the problem. This procedure can be repeated with samples of various mixture concentrations to reveal the thermal diffusivity as a function of temperature and concentration.

It should be mentioned that once this measurement is completed, the thermal conductivity can be obtained also, as can the density and specific heat.

Vapor-Liquid Equilibrium Curves

It should be noted that the generation of the vapor-equilibrium

curves for these mixtures should be easily accomplished also. This type of measurement is commonly done in teaching laboratories, and therefore should not present a great problem to obtain accurate data.

EXPERIMENTAL VERIFICATION

It is clear that the final step in the development of this predictive capability must receive some attention in this report. The predictive equation (15) was based on the assumption that the roughness and macro surface geometry were both sufficient to provide nucleation sites. The fluid adjacent to the surface is infinite in extent so that the bubbles are not impeded in their growth or movement by neighboring surfaces. To conduct the verifying experiments one must simulate this condition.

It is recommended that the initial set of experiments be conducted with single smooth tubes whose diameter is large compared to the typical bubble diameter. A variety of oil concentrations and surface heat fluxes must be investigated in the nucleate boiling regime. When this is complete to the satisfaction of the principal investigators, the effects of surface geometry for the single tube can be investigated, as can the effect of proximity of other tubes as found in tube banks. A systemmatic, step by step set of experiments can help develop an understanding of the physical phenomena that impact the heat transfer performance of the various

refrigerants.

Finally, it should be recommended that the choice of refrigerant for the first experiments should be one which has already been studied extensively. This will enable comparison to published data faster than if a new refrigerant were selected for the first experiments. It is clear that R-114 should be among the early refrigerants studied because of its current interest to the Navy. The recommended sequence of testing in order to maximize understanding would be single, smooth tubes followed by enhanced surfaces and tube banks.

CONCLUDING REMARKS

The search for new refrigerants that are environmentally safer than those currently used and which still perform well from a thermal perspective is very important. The problem of predicting nucleate boiling heat transfer preformance of refrigerant/oil mixtures has not been here-to-fore addressed except through the use of experimental techniques. This study has addressed the problem of finding a theoretical approach to this problem.

Three main studies were found that developed empirical expressions for the nucleate boiling heat transfer of refrigerant/oil mixtures. While these studies present useful expressions, they are based upon

experiments that must be done for each mixture so that one can be sure that the empirical coefficients are appropriate to the mixture. This need to run extensive experiments to develop the empirical expression for any new refrigerant-oil mixture clearly creates a hurdle in finding the new refrigerants.

To overcome this problem, the model being developed by Bajorek et al [13] was discussed. The advantage of this model is that it depends only on knowing the properties of the fluids of interest, and there are no empirical coefficients that need to be determined. The main weaknesses of this model are that it has only been tried out on a very small number of mixtures, and it does not include the effects of surface geometry. No refrigerant-oil mixtures have been examined with the model, so whether it properly accounts for the physics of the nucleate boiling process of these complicated mixutres, even on smooth surfaces, is still an open question.

The problem with trying this model is that we do not know the properties of the refrigerant-oil mixtures. The key property to determine is the mass diffusion coefficient, D_{12}. An experiment to determine this property is proposed. With this capability, coupled with the ability to measure the thermophysical properties of the mixtures, we should be able to predict the nucleate boiling heat transfer for any refrigerant-oil mixture. Refinements on this model also can be proposed once the initial evaluation tests are completed.

With an expression that relies only on knowing the properties of the mixture, we can predict performance with sufficient confidence to make sound judgements on the appropriateness of new refrigerants for use in Navy systems.

ACKNOWLEDGMENTS

The first author wishes to thank the Naval Postgraduate School for its support, and the many friends at NPS who made it such a pleasure to participate in this effort. Professor Marto, Professor Kelleher and Professor Healey deserve very special mention for all their efforts on behalf of the first author to enable this research to take place. The cooperation of Mr. R. Helmick, David Taylor Research Center is also much appreciated.

REFERENCES

1. A.S. Wanniarachchi, P.J. Marto and J.T. Reilly, "The Effect of Oil Contamination on the Nucleate Pool Boiling of R-114 from a Porous-Coated Surface".ASHRAE Trans., Vol.92, Pt.2, 1986, pp. 525-538.

2. S.M. McManus, P.J. Marto and A.S. Wanniarachchi, "Heat Transfer Enhancement in R-114 Water Chillers", ASME HTD-Vol.65,1986, pp. 11-19.

3. A.S. Wanniarachchi, P.J. Marto and L.M. Sawyer, "Effect of Oil on Pool Boiling Performance of R-114 from Enhanced Surfaces", Proc. ASME-JSME Thermal Engineering Joint Conference, Vol. 1, 1987, pp.531-538.

4. P.J. Marto and C.L. Anderson, "Nucleate Pool Boiling of R-113 in a Small Tube Bundle",Proc. ASME-JSME Thermal Engineering Joint Conference, 1991 (to be published)

5. S.M. Bajorek, J.R. Lloyd and J.R. Thome, "Evaluation of Multicomponent Pool Boiling Heat Transfer Coefficients", Proc. Int. Symp. Heat Transfer, August 1990, 6 pgs.

6. J.R. Thome, Enhanced Boiling Heat Transfer, Hemisphere Publishing Corp., 1990.

7. S. Chongrungreong and H.J. Sauer, Jr., "Nucleate Boiling Performance of Refrigerants and Refrigerant-Oil Mixtures",ASME J. Heat Transfer, Vol. 102, November 1980, pp.701-705.

8. K. Stephan and J. Mitrovic, "Heat Transfer in Natural Convection of Refrigerant-Oil Mixtures", Proc. 7th Int Heat Tranafer

Conference, Vol.4, 1982, pp. 73-87.

9. E. Hahne and A. Noworyta, "Calculation of Heat Transfer Coefficients for Nucleate Boiling in Binary Mixtures of Refrigerant-Oil", Int. Communications in Heat Mass Transfer, Vol. 11. No. 4, 417-429.

10. M.K. Jensen and D.L. Jackman,"Prediction of Nucleate Pool Boiling Heat Transfer Coefficiecnts of Refrigerant-Oil Mixtures", ASME J. Heat Transfer, Vol. 106, No.1, 1984, pp.184-190.

11. H.K. Forster and N. Zuber, "Dynamics of Vapor Bubbles and Boiling Heat Transfer", AIChE Journal, Vol.1, 1955, pp. 531-535.

12. S.M. Bajorek, "An Experimental and Theoretical Investigation of Multicomponent Pool Boiling on Smooth ond Finned Surfaces," Ph.D. Thesis, Department of Mechanical Engineering, Michigan State University, 1988.

13. S.M. Bajorek, J.R. Lloyd and J.R. Thome, "A Physics Based Model for Nucleate Pool Boiling of Milticomponent Mixtures," in Preparation.

14. E.U. Schlünder, "Heat Transfer in Nucleate Boiling of Mixtures", Proc. 8th Int. Conference on Heat Transfer, Vol. 5, 1986, pp. 2073-2079.

15. J.R. Thome and S. Shakir, "A New Correlation for Nucleate Pool Boiling of Aqueous Mixtures," AIChE Symposium Series, 1987, pp. 46-51.

16. D.L. Bidlack, "A Study of Binary Non-Ideal Nonassociating Liquid Solutions," Ph. D. Thesis, Department of Chemical Engineering, Michigan State University, 1964.

DISTRIBUTION LIST

Defense Technical Information Center
Cameron Station
Alexandria, VA 22314 — 2 Copies

Library, Code 0142
Naval Postgraduate School
Monterey, CA 93943-5100 — 2 Copies

Dean of Research
Code 08
Naval Postgraduate School
Monterey, CA 93943-5100 — 1 Copy

Mr. R. Helmick, Code 2722
David Taylor Research Center
Annapolis, MD 21402 — 1 Copy

Mr. J. Hanrahan, Code 2722
David Taylor Research Center
Annapolis, MD 21402 — 1 Copy

Mr. W. Noel, Code 56Y1C
Naval Sea Systems Command
Department of the Navy
Washington, D.C. 20362 — 1 Copy

Professor P.J. Marto
Dept. of Mechanical Engineering
Naval Postgraduate School
Monterey, CA 93943-5100 — 3 Copies

Professor J. R. Lloyd
Dept. of Mechanical Engineering
Michigan State University
A231C Engineering Building
East Lansing, MI 48824-1226 — 3 Copies